NASA TECHNICAL MEMORANDUM

NASA TM-77984

NASA-TM-77984 19860012186

EFFECT OF ADDITIONAL HEAT TREATMENT OF 2024-T3 ON THE GROWTH OF FATIGUE CRACK IN AIR AND IN VACUUM

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(NASA-TM-77984) EFFECT OF ADDITIONAL HEAT TREATMENT OF 2024-T3 ON THE GROWTH OF FATIGUE CRACK IN AIR AND IN VACUUM (National Aeronautics and Space Administration) 19 p HC A02/MF A01 CSCL 11F G3/26

N86-21657

Unclas 05792

Translation of "Invloed van het naveredelen van 2024-T3 op het Groeien van Vermoeiingsscheueren in Lucht en in Vacuum," Technische Hogeschool Delft, Luchtvaart en Ruimtevaarttechniek (Delft Technical University, Dept. of Aerospace Engineering), Report No. LR-237, Delft Netherlands, December 1976, pages 1-16, (N78-15255).

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON D.C. 20546 FEBRUARY 1986

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STANDARD TITLE PAGE

1. Report No. NASA TM-77984	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EFFECT OF ADDITIONAL HEAT TREATMENT OF 2024-T3 ON THE GROWTH OF FATIGUE CRACK IN AIR AND IN VACUUM		5. Report Date February 1986
		6. Performing Organization Code
7. Author(s) E.P. Louwaard		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASw- 4004
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Invloed van het naveredelen van 2024-T3 op het Groeien van Vermoeiingsscheueren in Lucht en in Vacuum", Technische Hogeschool Delft, Luchtvaart en Ruimtevaarttechniek (Delft Technical University, Dept. of Aerospace Engineering), Report No. LR-237, Delft Netherlands, December 1976, pages 1-16, (N78-15255).

16. Abstract

In order to determine the influence of ductility on the fatigue crack growth rate of aluminum alloys, fatigue tests were carried out on central notched specimens of 2024-T3 and 2024-T8 sheet material. The 2024-T8 material was obtained by an additional heat treatment applied on 2024-T3 (18 hours at 192 C), which increased the static yield strength from 43.6 to 48.9 kgf/sq mm. A change in the ultimate strength was not observed. Fatigue tests were carried out on both materials in humid air and in high vacuum. According to a new crack propagation model, crack extension is supposed to be caused by a slip-related process and debonding triggered by the environment. This model predicts an effect of the ductility on the crack growth rate which should be smaller in vacuum than in humid air; however, this was not confirmed. In humid air the crack-growth rate in 2024-T8 was about 2 times faster than in 2024-T3, while in vacuum the ratio was about 2.5. Crack closure measurements gave no indications that crack closure played a significant role in both materials. Some speculative explanations are briefly discussed.

17. Key Words (Selected by Author(s))		18. Distribution Statement Unclassified and Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22. Price

86N21657

CONTENTS

1. INTRODUCTION

[3] *

In a study previously carried out on the material 2024-T3, a growth rate of double was found for fatigue cracks as a consequence of the raising of the elastic limit through the "prestraining" of the material [1]. The prestressing was done by drawing the material 3% whereby $\sigma_{0.2}$ increased from 43.6 kgf/mm^2 to 48.9 kgf/mm^2 . As a consequence of this higher elastic limit less crack closure may be expected (the Elber-mechanism, [2]. This was confirmed by measurements, but only about a half of the faster crack growth could be attributed to a lower crack closing tension (lower σ_{cl} - higher ΔK_{eff}). It was postulated that the other half could be the result of higher tensions in the plastic crack tip zone. According to the VTH-model for crack growth (biblio. 3), the crack growth mechanism for this will be affected if growth of the crack takes place in an environment that is either more or less agressive than is found in the air of a laboratory. When the fracture growth occurs in an inert atmosphere then the mechanism is not (or not so greatly) affected.

The hypothesis outlined above formed the basis for the carrying out of some tests orientated towards tracing the influence of an elevated elastic limit on crack growth taking place in an inert environment. The raising of the elastic limit of the 2024-T3 material was,however,not brought about by stretching but rather by additional heat treatment of the T3 state to the T8 state. In

* Numbers in margin indicate foreign pagination

this report the results of some comparative tests are recorded and analyzed further in the discussion.

2. THE TEST PROGRAM

2.1. The material

We started with 2024-T3 Alclad plate material with a thickness of 2.5 mm. The additional heat treatment was carried out on the material by heating it for 18 hrs at 192^{o}C. The tension curves for the treated and untreated material are given in illustration 1.

2.2. The specimen type [4]

The tests were carried out on flat specimens with a central notch,see illustration 2. In the specimens tested in a vacuum the notches were created by means of sparks. In the remaining specimens they were created with the help of a jewellers saw.

2.3. The fatigue loading

The crack growth tests were carried out with a loading at a constant amplitude of $\sigma_m \pm \sigma_a = 11 \pm 4$ kgf/mm^2. A high value of σ_{min} was chosen in the hope that crack closing would then not take place or be as minimal as possible. Without crack closing $\Delta K_{eff} = \Delta K$. A possible effect of the ductility (T8 in comparison with T3) or environment will thus be not to have an indirect influence because of a different crack opening tension.

2.4. The environment

the tests were carried out in an inert atmosphere (vacuum $< 10^{-6}$ Torr) and a non-inert atmosphere (air, relative humidity $\sim$ 50%, temp. $\sim + 20^{\circ}C$). As has already previously been mentioned in the introduction it was anticipated that the ductility (T8 compared to T3), which had such an unfavorable effect on the crack growth rate in the laboratory atmosphere, would be much reduced in an inert atmosphere.

3. THE CARRYING OUT OF THE TESTS AND THE RESULTS

3.1. The crack growth tests

The tests were carried out on the 20 ton electro-hydraulic Amsler material testing machine of the department b2, see illustration 3. For the tests that were carried out in a vacuum,use was made of the vacuum cell developed in the b2 laboratory. The emptying pumps of this vacuum cell can achieve as low a pressure as 10^{-7} Torr with for instance a rotary prepump (Beltzer) and an oil diffusion pump (Beltzer). The fatigue cracks of the specimen plates to be tested in the vacuum were started in laboratory air in view of the very long initial timelength in a vacuum. The crack expansion was [5]
measured as a function of the total changes with the aid of a stereoscopic microscope. The performance results were recorded in a special report. (illustration 6.)

From this data the crack growth speed was calculated from

$$(da/dN)_{a=a_i} = \frac{a_{i+1} - a_{i-1}}{N_{i+1} - N_{i-1}}$$

in which

i = observation number

a = half the crack length

N = number of changes

For the calculation of ΔK for working out the final width of the specimen plate, use is made of the Federson correction factor where:

$$\Delta K = \Delta S \cdot \sqrt{\pi a} \cdot C_{Fedd}$$

where:

$\Delta S = \Delta 2x$ tension amplitude

$$C_{Fedd} = \sqrt{\sec \frac{\pi a}{2b}}$$

in which

b = half the plate width

The results are set out in the illustrations 4 and 5. The averaged curves are given in illustration 6.

3.2. The crack closing measurements. The crack closing measurements were carried out with a COD meter (illstration 1,4) with a measuringlength of 4 mm. This was placed about 2 mm behind the crack front. The principle of the measurement is [6]
outlined in illustration 7. The dynamometer of the Amsler-machine provides the signal for the tension σ of the specimen plate. The tension level at which crack closing begins (at reduced σ) or at which crack opening is complete (at increased σ) is determined as being the transition point of the non-linear part of the recording to the fully linear part (illustration 7).

Although in other test series the crack closing tension was easily perceptible in the method outlined above, the measurements here gave only weak and not completely clear indications of the occurrences of crack closing between σ_{min} and σ_{max}. This was equally true for the T3 material as well as for the T8 material. The indications suggest that crack closing did not occur between σ_{min} and σ_{max} or closeby.
The indications are in either case insufficient to consider

these as a definite explanation, for on the other hand there is the difference between the results in air and in a vacuum.

3.3. Fractographic observations

There were only macroscopic observations made. Therefore it was obviously difficult to report a transition point for crack growth in the T8 material in air, because the macroscopic turning of the fracture front was preceded by multiple shear. In the T3 material it was definitely possible to talk of a transition point (illustration 8). The general tendencies for the transition points are shown in illustration 6.

From the tests carried out in the vacuum it did not appear possible to obtain a transition point, because right from the start of the crack widening in the vacuum (after initiation in air) the crack lines clearly showed multiple shear. A clear transition into crack widening in the single- (or double-) shear mode was therefore not obtainable either (illustration 8).

4. DISCUSSION [7]

From illustration 6 two tendencies can be clearly seen:

1. The crack growth speed in the 2024-T8 material is about twice as high as in the 2024-T3 material. In air it is somewhat less than twice and in the vacuum somewhat more than twice. The result for air is in agreement with the data provided by

Broek [5].

2. The crack growth rate in air is clearly higher than in a vacuum. This is true for both materials. This influence of the surroundings is smaller with a high value of ΔK, which agrees with the general tendencies, such as can be found in different places in the bibliography.

The results did not confirm the conjectures expressed in the introduction, that the greater or lesser degree of ductility of the material in an inert atmosphere would be of less significance. The difference between the T3 and T8 material is in the vacuum itself somewhat greater. The conjecture was based on the idea that at the tip of the crack in the T8 material it was true that a higher stress tension was created, but because of the absence of an agressive environment this would not be able to lead to a greater part in the crack widening. It is obvious that there is more to it than meets the eye.

From the results obtained little of a concrete nature can be said; however some more speculative arguments can be mentioned:

1. The crack closing measurements at present do not form a basis on which to make a statement, because crack closing could not genuinely be demonstrated to have taken place. That is not to say that it may not have occurred to some very slight degree, either in the air or in the vacuum. Then the T3 material would be at greatest advantage due to its greater ductility which would give rise sooner to crack closing.
2. In the VTH model the function of the pulling tension in the area of the crack tip in an agressive environment (i.e. air)

is associated with the increasing of the crack growth through "debonding". Crack growth through "debonding" and through slipping are complementarily assumed. The translation of slip motion into crack widening should be reinforced through the pulling tension in an inert environment. [8]

3. Finally the difficult correlation between the size of the plastic zone (dependent upon the ductility) and the distribution of the plastic deformation in that zone must be mentioned (as well as dependency on ductility). Thereby "cracktip-blunting" could play a role; likewise then the T8 material in the vacuum would remain a disadvantage. It cannot be excluded that the crack tip geometry is different in air and in a vacuum. The contribution of the slips to fracture widening should itself be fundamentally different in air and in a vacuum.

The specialized tests still leave obvious room for reinterpretation. In order for further defining of the mechanism to be made,it appears that the following are necessary:

(a) There must be something with more certainty said about crack closing, because K_{eff} is still a first base for making comparisons.

(b) With more refined programs of loading,more concise information about what happens at the fracture tip can be compiled.

(c) fractographic research at the micro-level is essential. The

character of the growth lines (brittle or ductile striations) should be mentioned in this context.

5. CONCLUSIONS

The less ductile behavior of the material Aluminium 2024-T8 with respect to the more ductile 2024-T3 material both in laboratory air as well as under vacuum conditions gives rise to a higher crack tip growth rate as a consequence of a higher level of tension in the direct surrounding of the crack tip. A clear image of why this also leads to a higher crack growth rate demands still more accurate fractographic observations and crack closing measurements.

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/9

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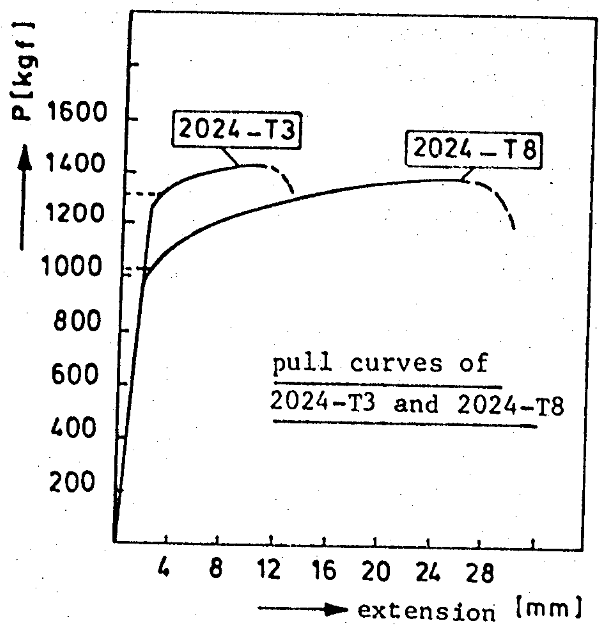
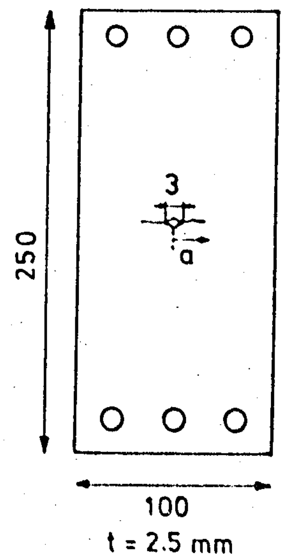
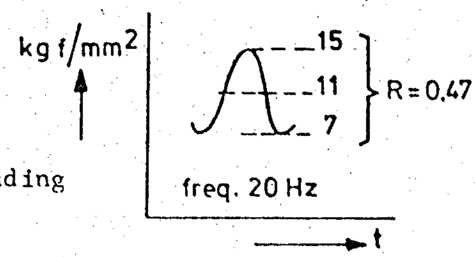


	$\sigma_{0.2}$ [kg/mm²]	σ_{br} [kg/mm²]	δ [%] starting length : 50 mm
T3	33.5	45.3	18.9
T8	40.6	45.9	12.4

Figure 1. Effect of the heat treatment on the mechanical properties

/11





environment	2024-T3 Alclad	2024-T8 Alclad
	no. of tests	
Vacuum ($\sim 5\times10^{-7}$ torr)	2(L1, L2)	2(K1, K2)
air (R.H~50%)	2(G1, G2)	2(H1, H2)

Figure 2. Summary of the crack growth tests

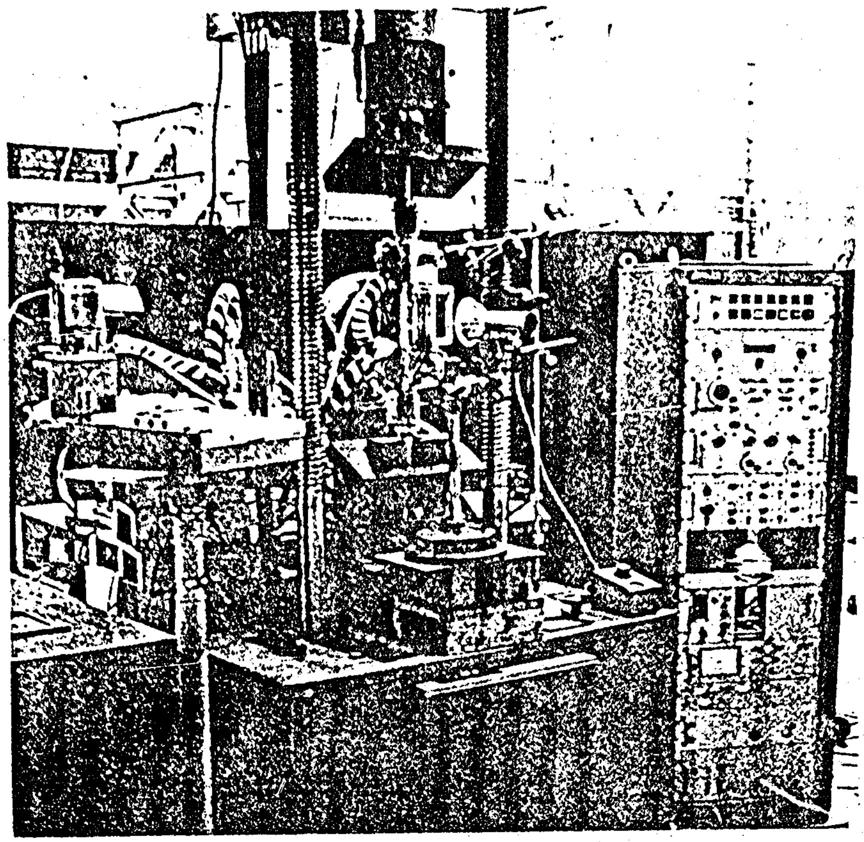


Figure 3. The 20-ton Amsler testing machine with a vacuum cell, illumination and binocular microscope.

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/13

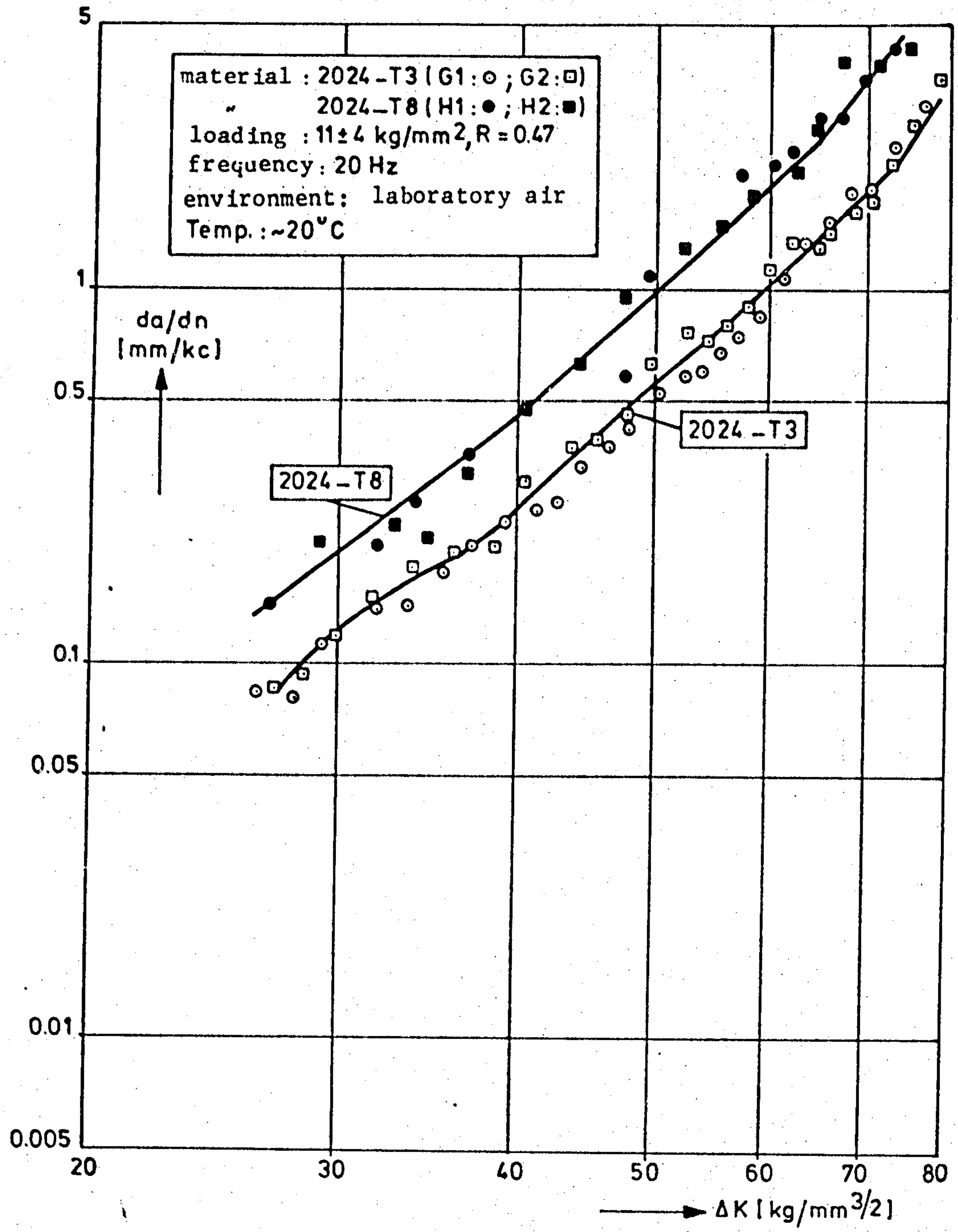

Figure 4. Crack growth rates in air

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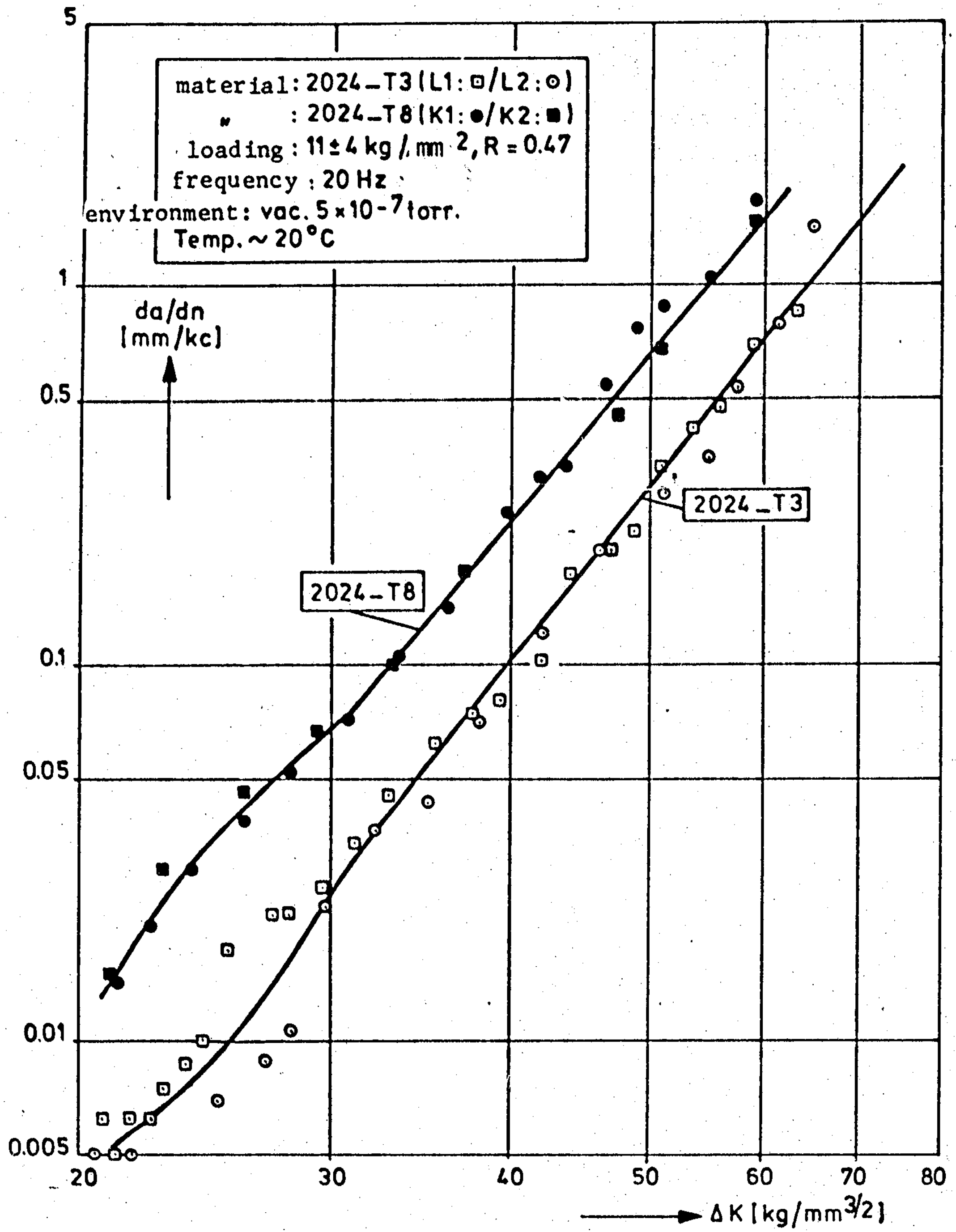

Figure 5. Crack growth rates in the vacuum

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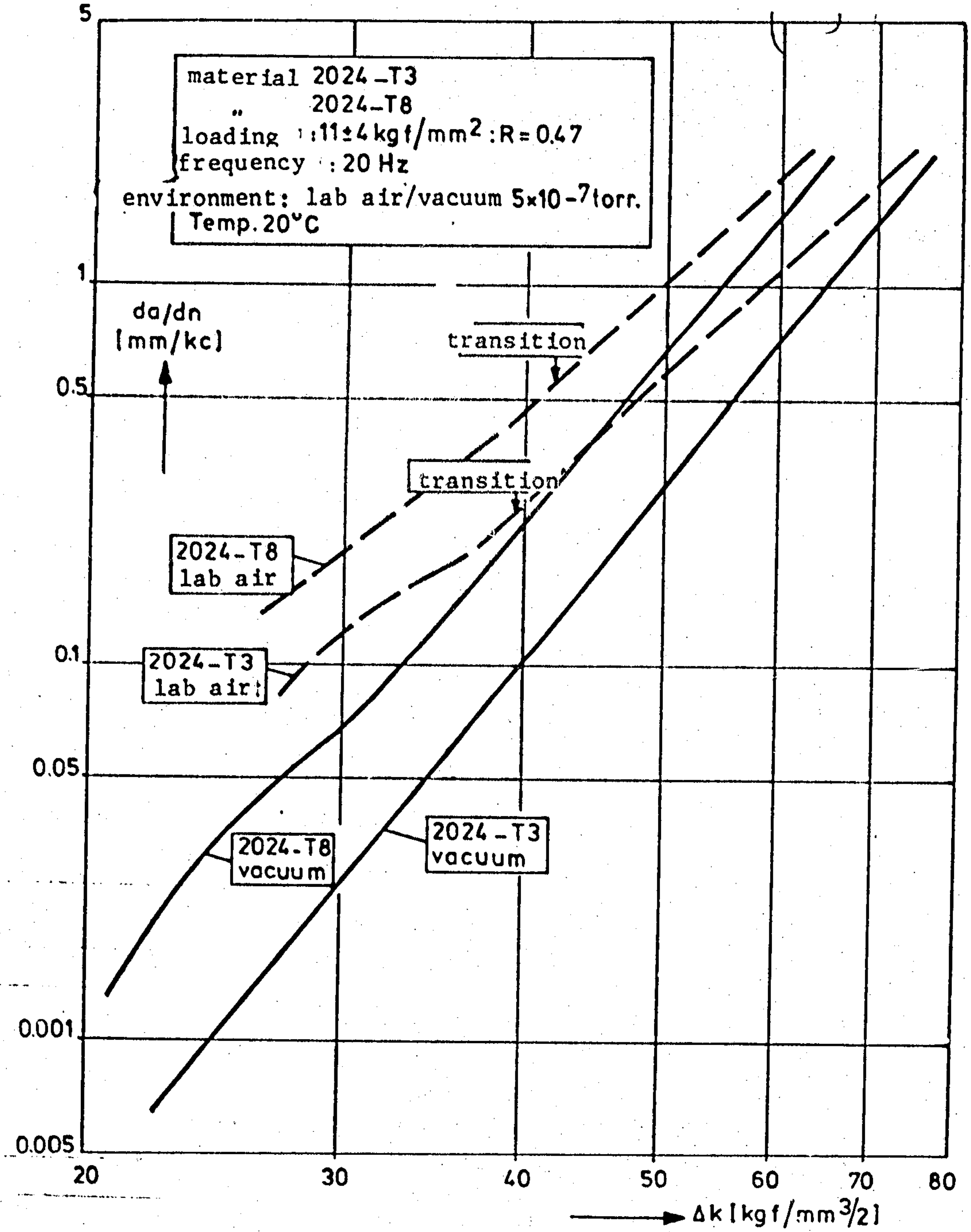

Figure 6. Crack growth rates in air and in the vacuum

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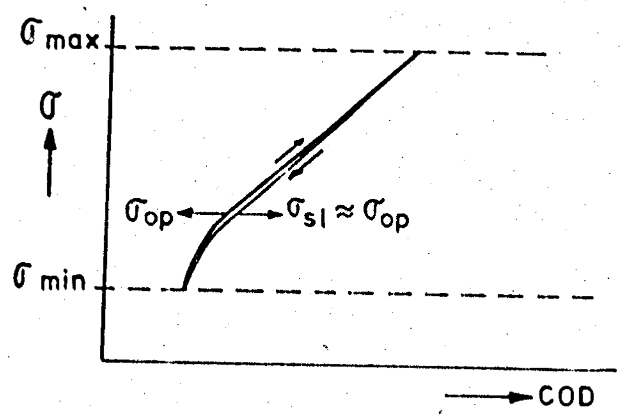

Figure 7. Principle for the determination of the tension level at which crack closure occurs

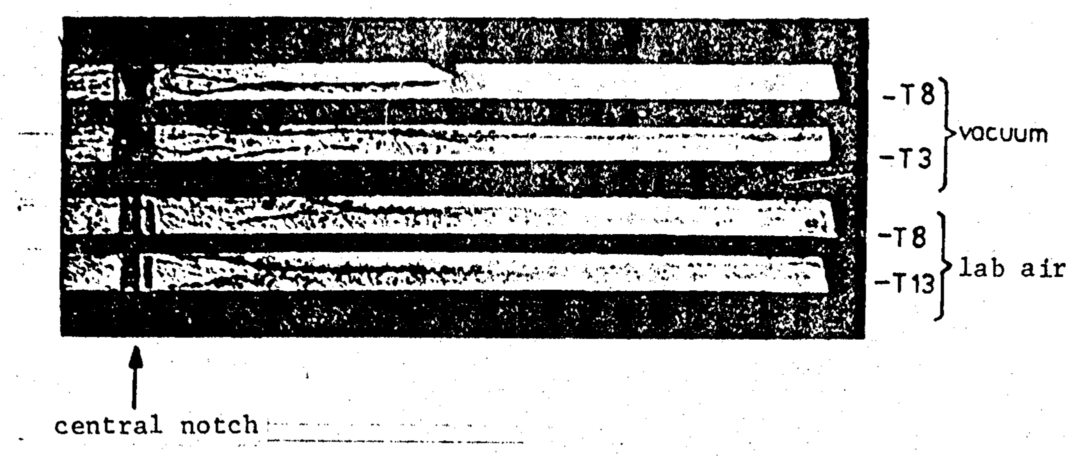

Figure 8. Fractures caused in 2024-T3 and 2024-T8 in a vacuum and in air (1.8x magnification)